Probing Neutron Star Physics with NANOGrav and Other Millisecond Pulsars

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Pulsar Timing

• Unambiguously account for every single rotation of a pulsar

• If we can predict times of arrival (TOAs), we know when external effects are interfering (ISM, Shapiro delay, ephemeris, gravitational waves!)

• Can obtain 5 Keplerian parameters ($P_{\text{orb}}$, $e$, $asin(i)/c$, $T_0$, $\omega$) with normal timing measurements

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Shapiro Delay

Shapiro Delay in NANOGrav & Other MSPs

NRAO

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• Highly inclination-dependent

• High-mass companions make higher orbital inclinations likely, which generate larger Shapiro signals

• Observations difficult because of the need for specific windows and accurate timing solutions

• Residuals ~10 μs
Shapiro Delay

\[ s = x \left( \frac{P_b}{2\pi} \right)^{-2/3} T_{\odot}^{-1/3} M^{2/3} m_c^{-1} \]

\[ r = T_{\odot} m_c \]

\[ T_{\odot} \equiv \frac{GM_{\odot}}{c^3} = 4.925490947 \mu s \]

\[ M \equiv m_p + m_c, \quad x \equiv a_p \sin i / c, \quad s \equiv \sin i \]

\[ f(m_p, m_c) = \frac{4\pi^2}{G} \frac{(a \sin i)^3}{P_b^2} = \frac{(m_c \sin i)^3}{(m_p + m_c)^2} \]

Demorest et al. 2010, *Nature*, 467, 1081D

Full Shapiro Signal
Shapiro Analysis of NANOGrav MSPs

- Fonseca et al. 2016

- 24 binaries in 9-year data release; 14 show significant SD; 4 new measurements

- MSP masses between 1.18 and 1.93 $M_\odot$ (J1614-2230)

- Most valuable measurements are of highest-mass NSs
Shapiro Analysis of NANOGrav MSPs

Red = New measurement

Purple = Much improved measurement

Orange = $\dot{\omega}$ included (rate of periastron advance)
What Can NS Masses Tell Us?

- Poorly understood EOS
- Exotic physics at hyper-atomic densities
  - Various issues, including the “hyperon problem” ($M_{\text{max}} = 1.38 M_\odot$) (Bombaci 2015)
  - M-R relationship is asymptotic, so every small increase in mass is revolutionary
What Can NS Masses Tell Us?

- The case of PSR J1614–2230 (Demorest et al. 2010), included in NANOGrav survey:
  - 1.97 $M_\odot$ (now measured at 1.93); highest-mass NS at the time; now have J0348+0432: 2.01 $M_\odot$ (Antoniadis et al. 2013)
  - Constrained NS equation of state greatly (no exotic/strange quark matter)
  - (Aside: most-cited GBT paper)
- Sheds light on distribution of NS masses (bimodal? Antoniadis et al. 2016)
- Are heavy NSs “born massive” or do they accrete matter above the 1.4 $M_\odot$ mark?
• Systems that show significant Shapiro delay are rare; have to probe every possible system
• Continue to monitor NANOGrav Shapiro binaries
• J0721-2038
  • Great candidate – high companion mass, similar to J1614–2230, should time to ~5 μs
• Many future telescopes (SKA, NICER) will be instrumental in these studies
Conclusions

• Shapiro delay studies are a great product of the NANOGrav collaboration’s continued timing of ~50 MSPs

• 14 significant Shapiro delay measurements, yielding inclinations and (most importantly) masses from NANOGrav 9-year data set

• High-mass NSs help constrain EOS

• We will continue to study every available system with existing instruments (GBT, AO) and future telescopes (SKA, FAST)

Thank you!